Summit on Management of Radiation Dose in CT:
Toward the Sub-mSv Exam
Bethesda North Marriott, Feb. 24-25, 2011

Innovations Required in Hardware

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Disclosures

- WAK is a consultant to
  Siemens Healthcare, Erlangen, Germany
- WAK is founder and shareholder of
  Artemis Imaging GmbH, Erlangen, Germany
- WAK is a firm believer in the future of CT.

Innovations Required in Hardware

- Definition of goals
- X-ray sources
- X-ray detectors
- Dose management
- X-ray beam collimation
- Conclusions

Estimates of effective dose in CT

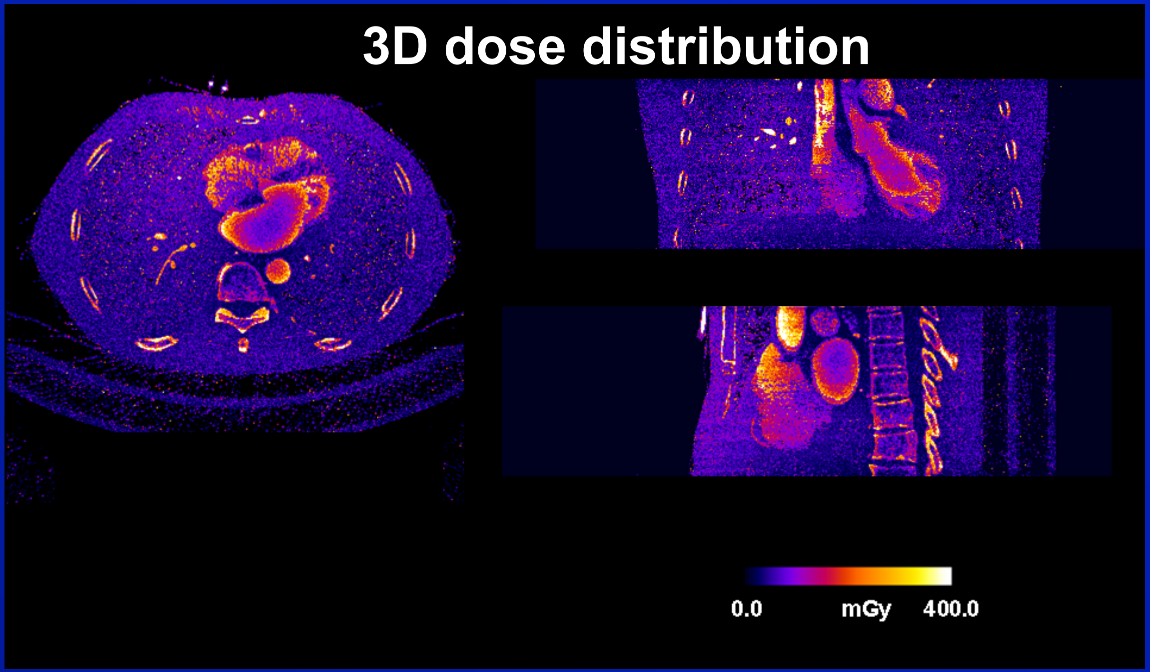
Table 13: Mean effective doses for the 'Top 20 Exams' in the ten DOSE DATAMED countries

Exam type	LU -	BE 00-05	DE 92-05	NO 85-95	CH 1998	FR 01-03	SE 1995	DK 1995	NL 2002	UK 90-01	Max Min
	Mean E per examination (mSv)										
13. CT head	2.6	2.3	2.6	1.8	2.2	1.8*	2.0	1.9	1.2	2.0	**2.2**
14. CT neck	2.5	-	2.5	3.4	3.1	2.5*	-	1.3	-	2.4	**2.6**
15. CT chest	10.0	4.1	7.6	11.5	8.8	5.5*	-	11.0	5.5	7.8	**2.8**
16. CT spine	9.0	-	2.9	4.3	9.1	4.0*	-	5.7	3.1	4.2	**3.1**
17. CT abdomen	15.0	11.3	18.6	12.6	8.4	5.8*	-	14.0	10.6	9.8	**3.2**
18. CT pelvis	-	-	10.6	9.3	7.0	-	-	8.3	7.4	9.8	**1.5**
19. CT trunk	7.9	-	24.4	-	-	-	10	15.0	-	10.4	**3.1**
All CT	**7.4**	**7.7**	**8.1**	**6.1**	**6.0**	**3.5***	**6.0**	**5.9**	**5.3**	**5.4**	**2.3**

Natural background radiation: 3 mSv/y.
(range: 1-10 mSv/y.)

EC Radiation Protection Report N° 154, 2008

Estimates of effective dose in CT



If dose distribution is known
➡ Organ dose and eff. Dose E

Scan parameters (CTDI, DLP) are known
➡ k = E/DLP

In general: Effective Dose E = k×DLP

ORIGINAL RESEARCH ■ MEDICAL PHYSICS

Radiology

Multisection CT Protocols: Sex- and Age-specific Conversion Factors Used to Determine Effective Dose from Dose-Length Product[1]

Paul D. Deak, PhD
Yulia Smal, MSc
Willi A. Kalender, PhD

Conversion factors CF to estimate effective dose *E* from the dose length product *DLP* for modern scanners using the ICRP 103 tissue weighting factors.

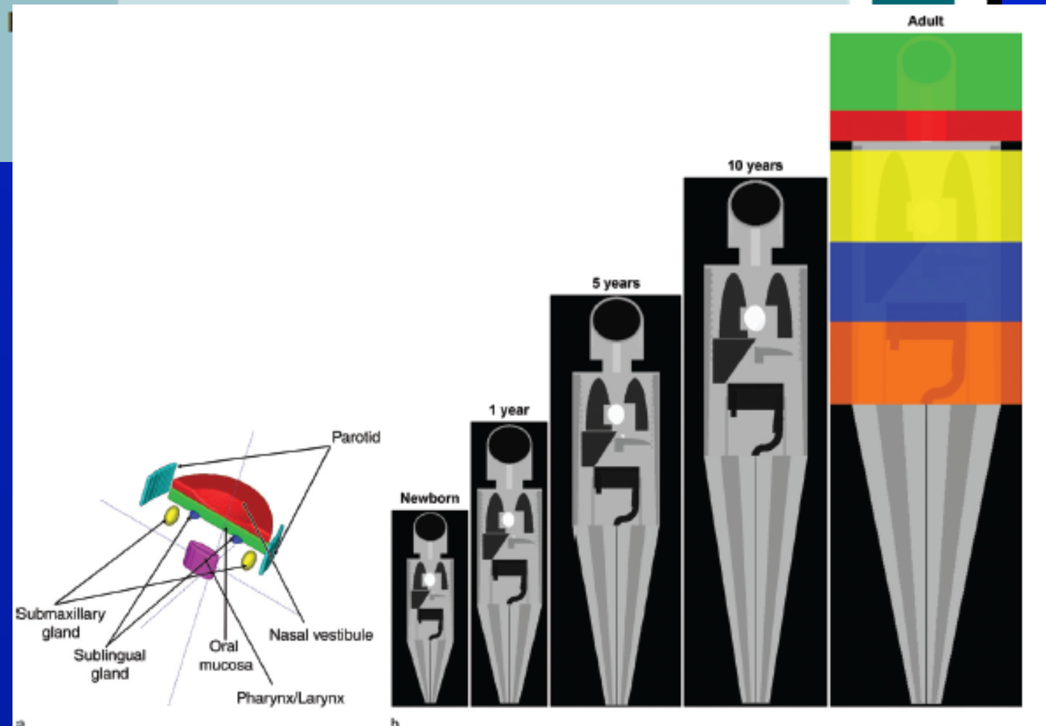
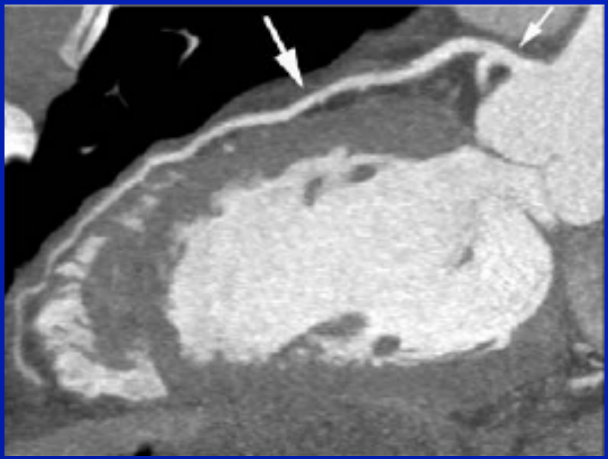
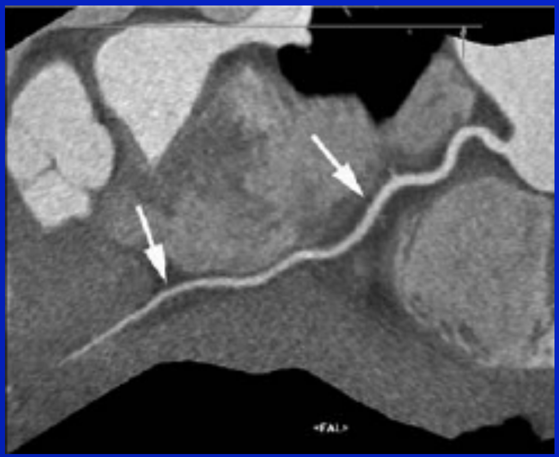


Figure 1: (a) The organs in the head and neck that were newly given weighting factors in ICRP publication 103. The organs were defined as ellipsoids, cylinders, or spheres, as in the original description by Cristy and Eckerman (12). (b) The ORNL phantom series used for computation of conversion factors. Colors = scanned regions in adult phantoms. (For simplicity, scanned regions are shown only for the adult phantoms. The same region landmarks were used for the pediatric phantoms.) The original phantoms contain all the necessary organs used for computation of effective dose as defined in ICRP publication 60.

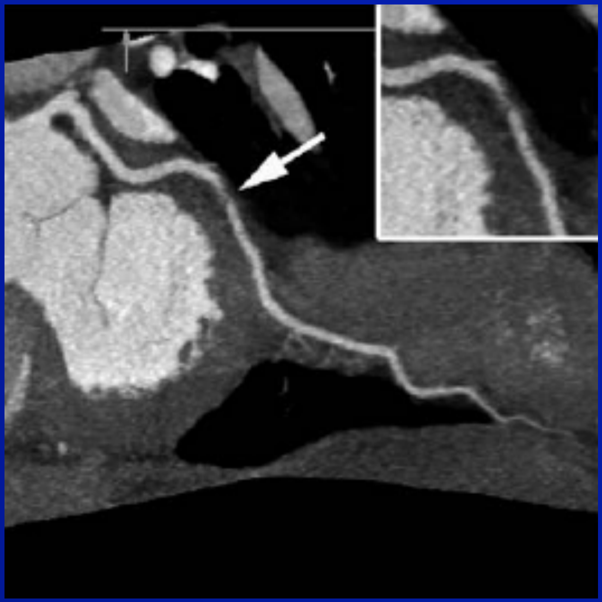
Deak P, Smal Y, Kalender W. Radiology 2010; 257:158-166

Dual Source CT at high pitch





- 63 y, male, 57 b.p.m.
- Pitch 3.2
- E = 0.84 mSv



EUROPEAN SOCIETY OF CARDIOLOGY®

European Heart Journal (2010) **31**, 340–346
doi:10.1093/eurheartj/ehp470

CLINICAL RESEARCH
Imaging

Coronary computed tomography angiography with a consistent dose below 1 mSv using prospectively electrocardiogram-triggered high-pitch spiral acquisition

Stephan Achenbach[1]*, Mohamed Marwan[1], Dieter Ropers[1], Tiziano Schepis[1], Tobias Pflederer[1], Katharina Anders[2], Axel Kuettner[2], Werner G. Daniel[1], Michael Uder[2], and Michael M. Lell[2]

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State of the Art & Goals

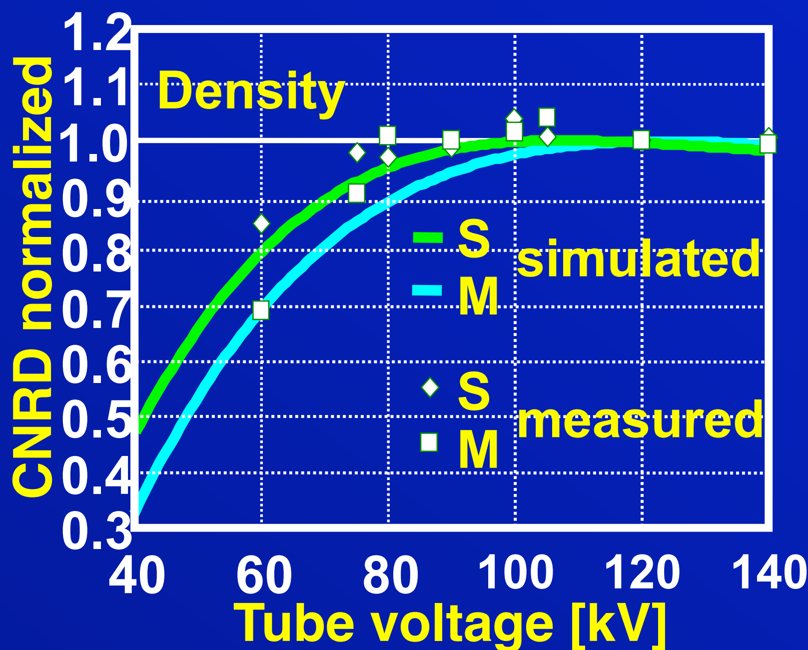
- Sub-mSv scanning has become a reality for a few applications already, e.g. in cardiac and pediatric CT.
- Effective dose in CT is quoted typically as 1 to 10 mSv per exam. I here assume an average value of 5 mSv.
- To reach the goal of sub-mSv scanning in general would require a reduction by at least a factor of 5, e.g. from 100 % = 5 mSv to 20 % = 1 mSv!

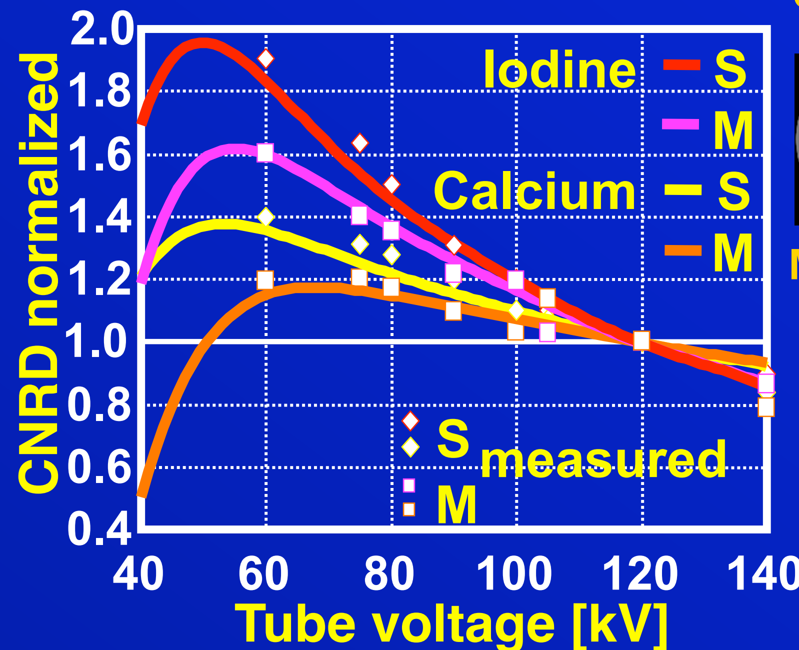
Innovations Required in Hardware

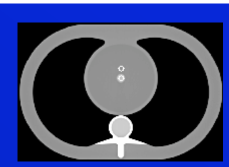
- Definition of goals
- X-ray sources
  - optimal spectra
  - requirements on power & filtration
- X-ray detectors
- Dose management
- X-ray collimation

Spectral Optimization for Thoracic CT

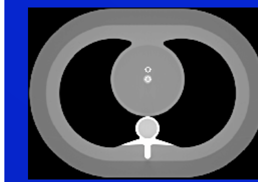
Simulations and Measurements







S: 300 x 200

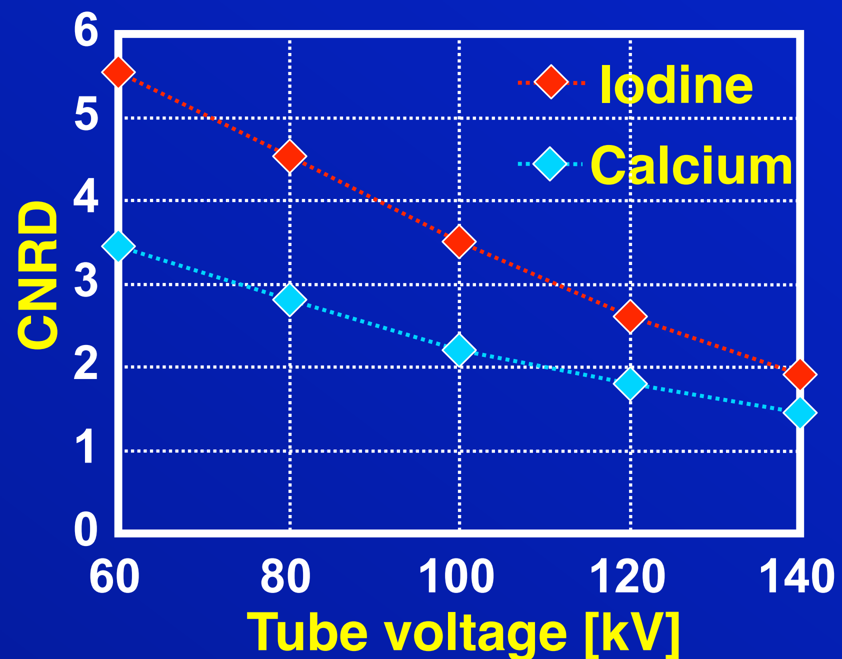


M: 350 x 250

Contrast due to	Density		Iodine		Calcium	
Size	S	M	S	M	S	M
Optimum tube voltage	110 kV	120 kV	50 kV	60 kV	50 kV	70 kV
Change in dose at const. CNR 120 kV → 80 kV	+ 9 %	+ 21 %	- 53 %	- 45 %	- 37 %	- 24 %

Kalender et al. Med Phys 2009; 36:993-1007

Spectral Optimization for Pediatric CT
Cadaver Measurements



Contrast due to	Iodine	Calcium
Optimum tube voltage	< 80 kV	< 80 kV
Change in dose at const. CNR 120 kV → 80 kV	- 67 %	- 62 %

Kalender et al. Med Phys 2009; 36:993-1007

Conclusions on spectra

- Adapt the spectrum to the task and to the size of the patient to be imaged.
- There is an amazingly high potential for dose reduction by spectral optimisation.
- Higher pre-filtration helps reduce dose.
- Demands on x-ray power will increase considerably.

Dose reduction potential

	%	factor
• X-ray sources	20	0.8
• X-ray detectors		
• Dose management		
• X-ray beam collimation		

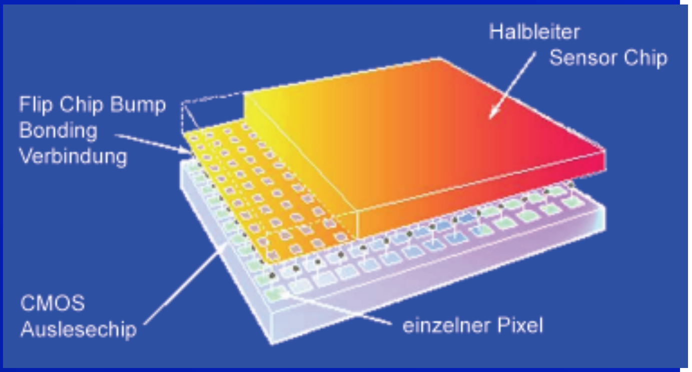
Innovations Required in Hardware

- Definition of goals
- X-ray sources
- X-ray detectors
- Dose management
- X-ray beam collimation
- Conclusions

Goals for detector developments in CT

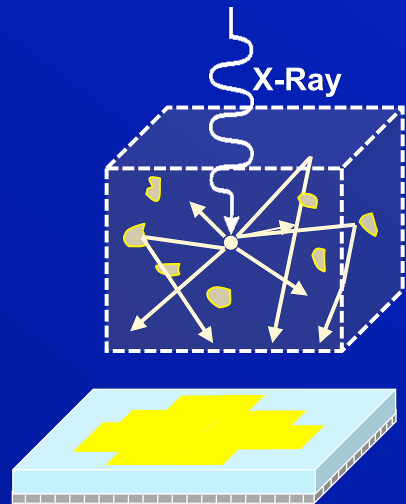
- Efficiency close to 100%
  for x-ray absorption and for geometry
- High spatial & temporal resolution
- Single photon counting
- Energy discrimination
- Direct conversion of x-rays
  to electric signal

e.g.,
Medipix detector
CdZTe sensor
3 energy levels

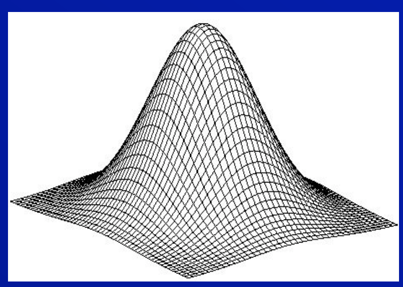


Detection principles

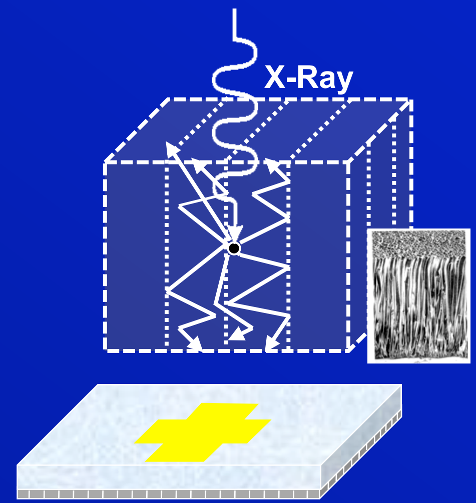
Scintillator



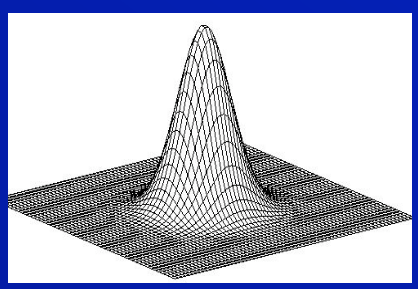
Photodiode + Transistor array



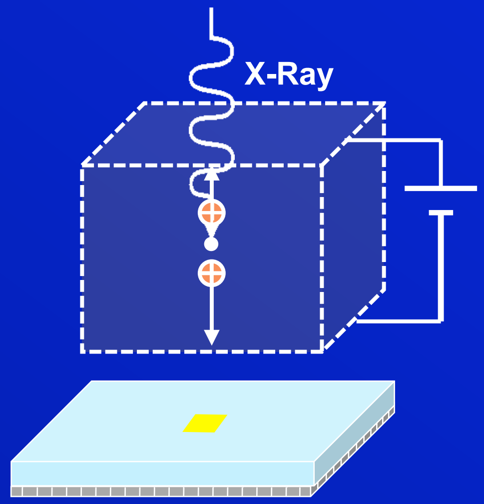
Scintillator (structured)



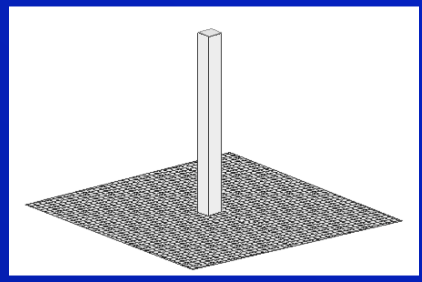
Photodiode + Transistor array



Direct converter

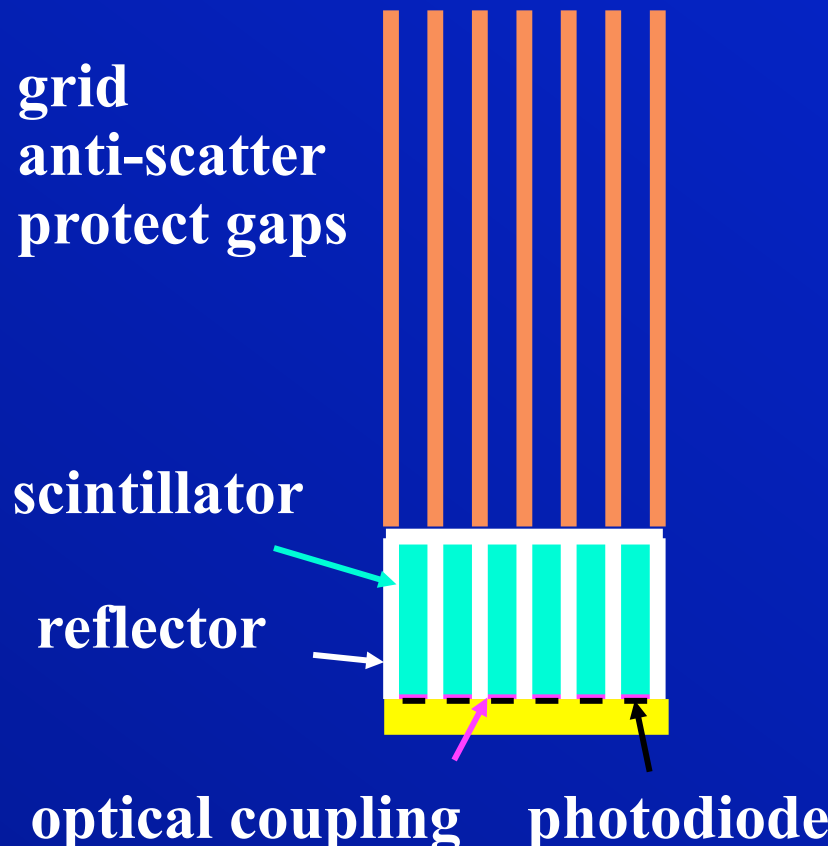


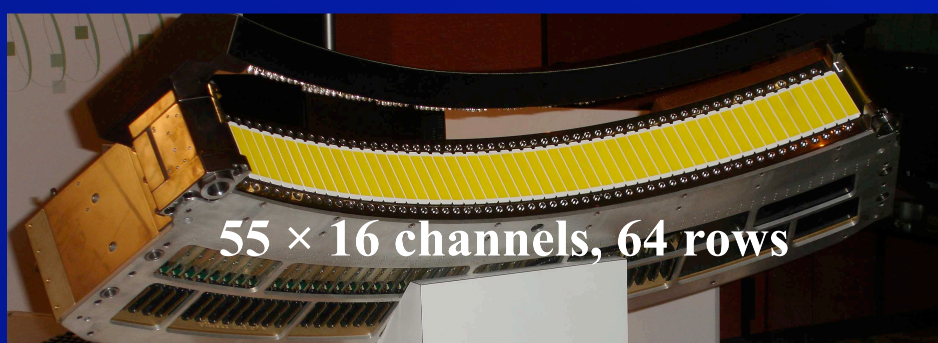
Transistor array

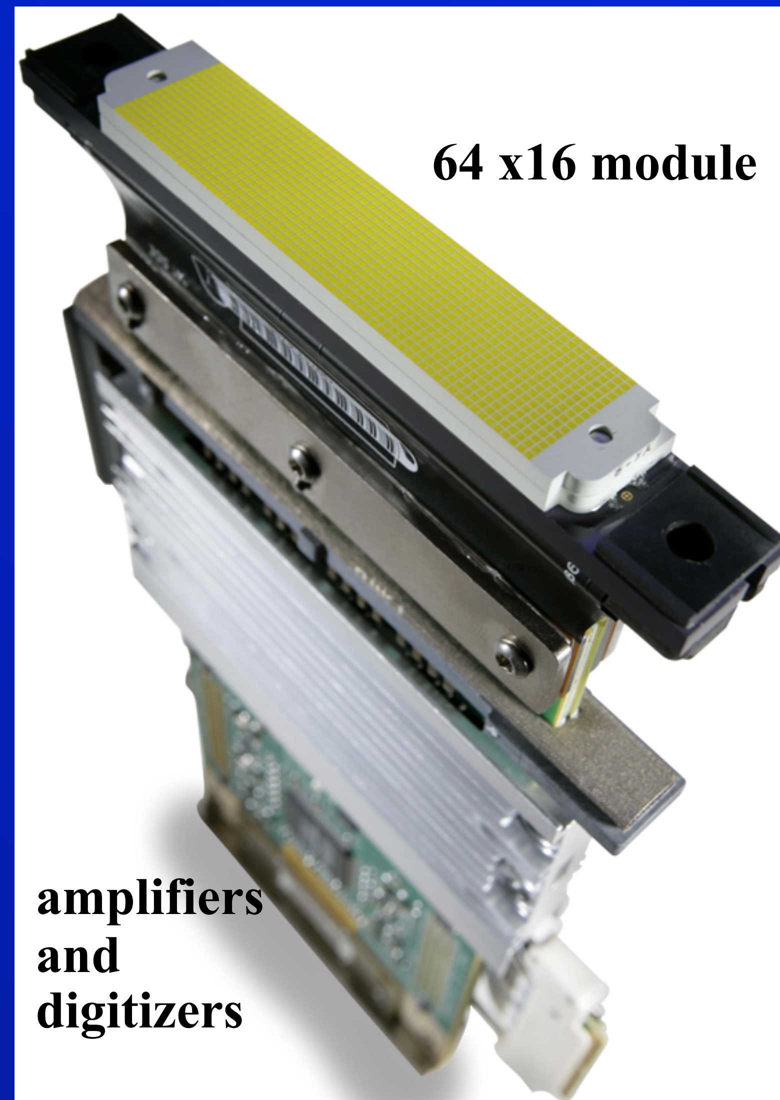


Point Spread Functions (PSF)

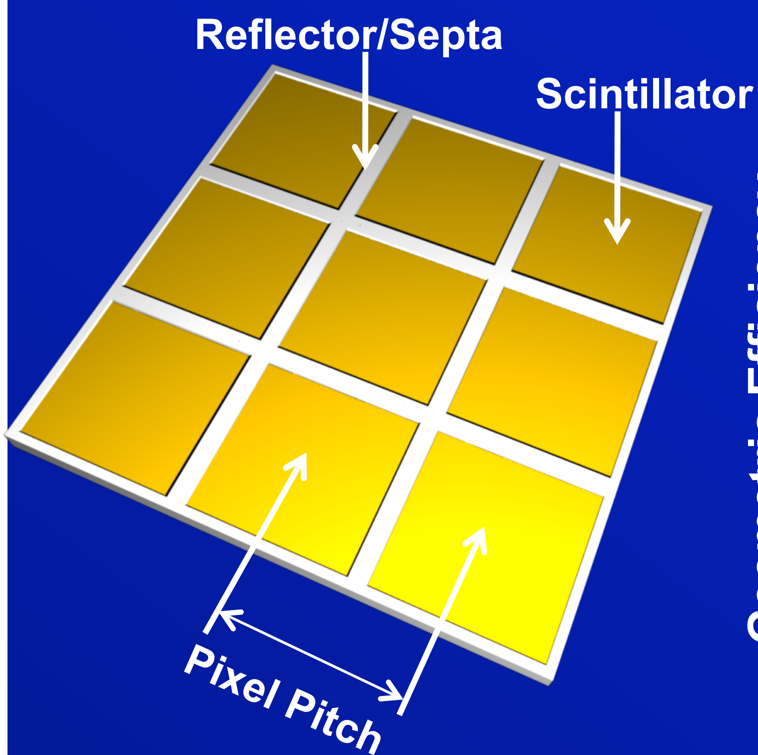
Standard 64-slice Multi-Row CT detector

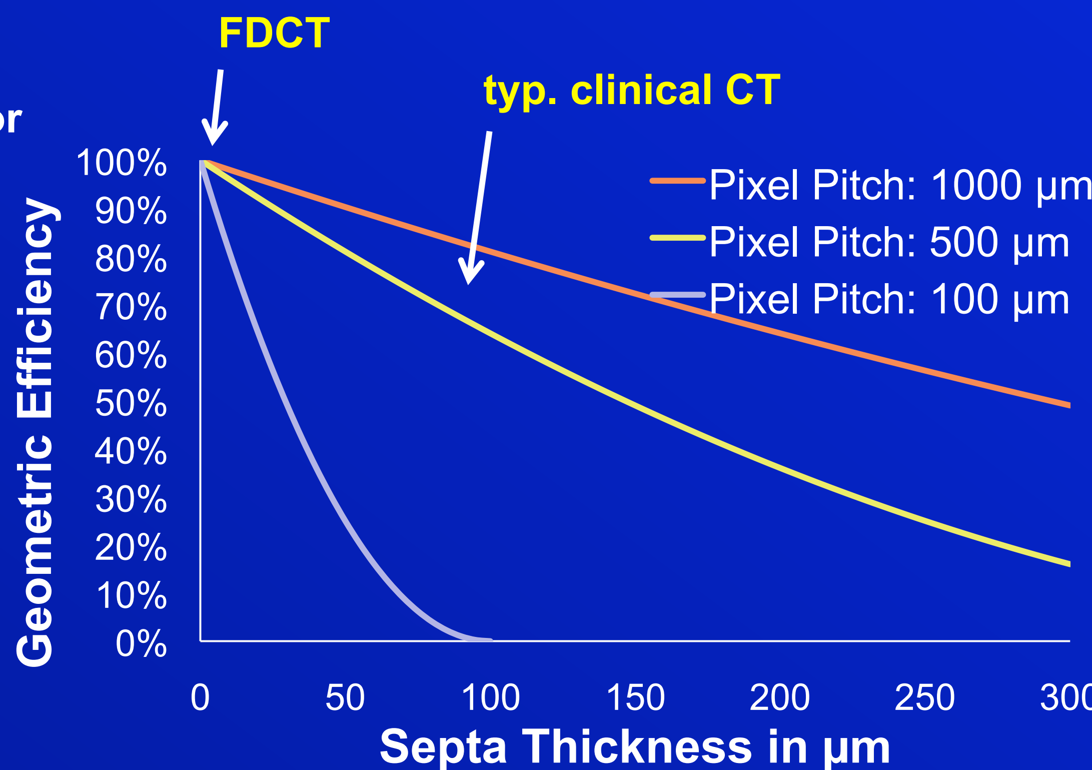






Geometric efficiency





Flat detectors can offer 100% geometric efficiency since there are no discrete detector pixels and septa.

Absorption efficiency, %

	Attenuated spectrum [illegible]					
Detector material	CsI		CdTe		GOS	
Tube voltage	80 kV	120 kV	80 kV	120 kV	80 kV	120 kV
Thickness 1.00 mm	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
1.40 mm	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

Dose reduction potential

	%	factor
• X-ray sources	20	0.8
• X-ray detectors	30	0.7
• Dose management		
• X-ray beam collimation		

Innovations Required in Hardware

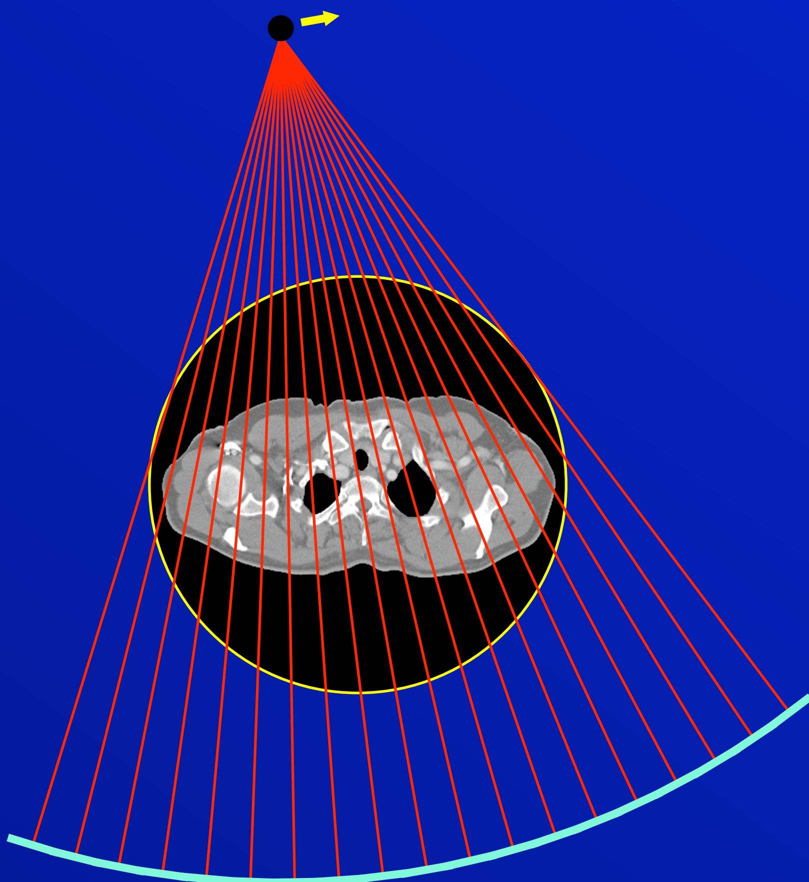
- Definition of goals
- X-ray sources
- X-ray detectors
- Dose management
  - tube current modulation (TCM)
  - automatic exposure control (AEC)
  - choice of spectra
- X-ray beam collimation
- Conclusions

Tube current modulation (TCM)

introduced in the late 1990ies
and generally available today.

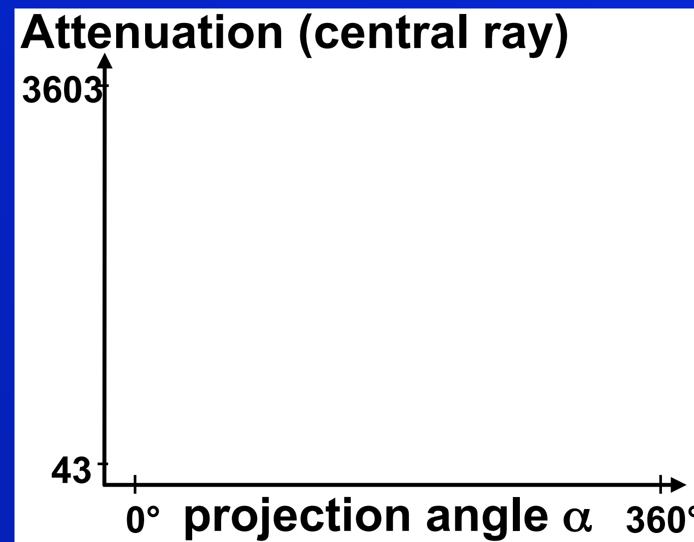
The principle simply is:
Adapt the tube current and thereby the x-ray intensity to the attenuation given for any projection as a function of rotation angle α and position z.

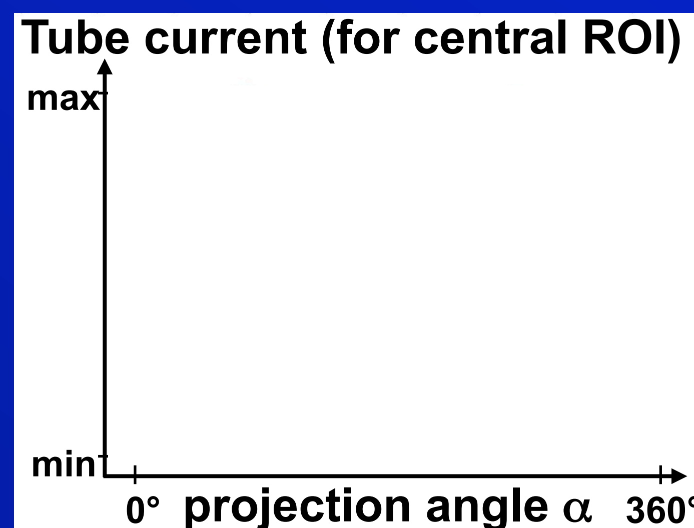
In-plane or rotational TCM (α-TCM)



Attenuation for the central ray:

in a.p. direction: 43
in lateral direction: 3603





mAs Reduction by Tube Current Modulation

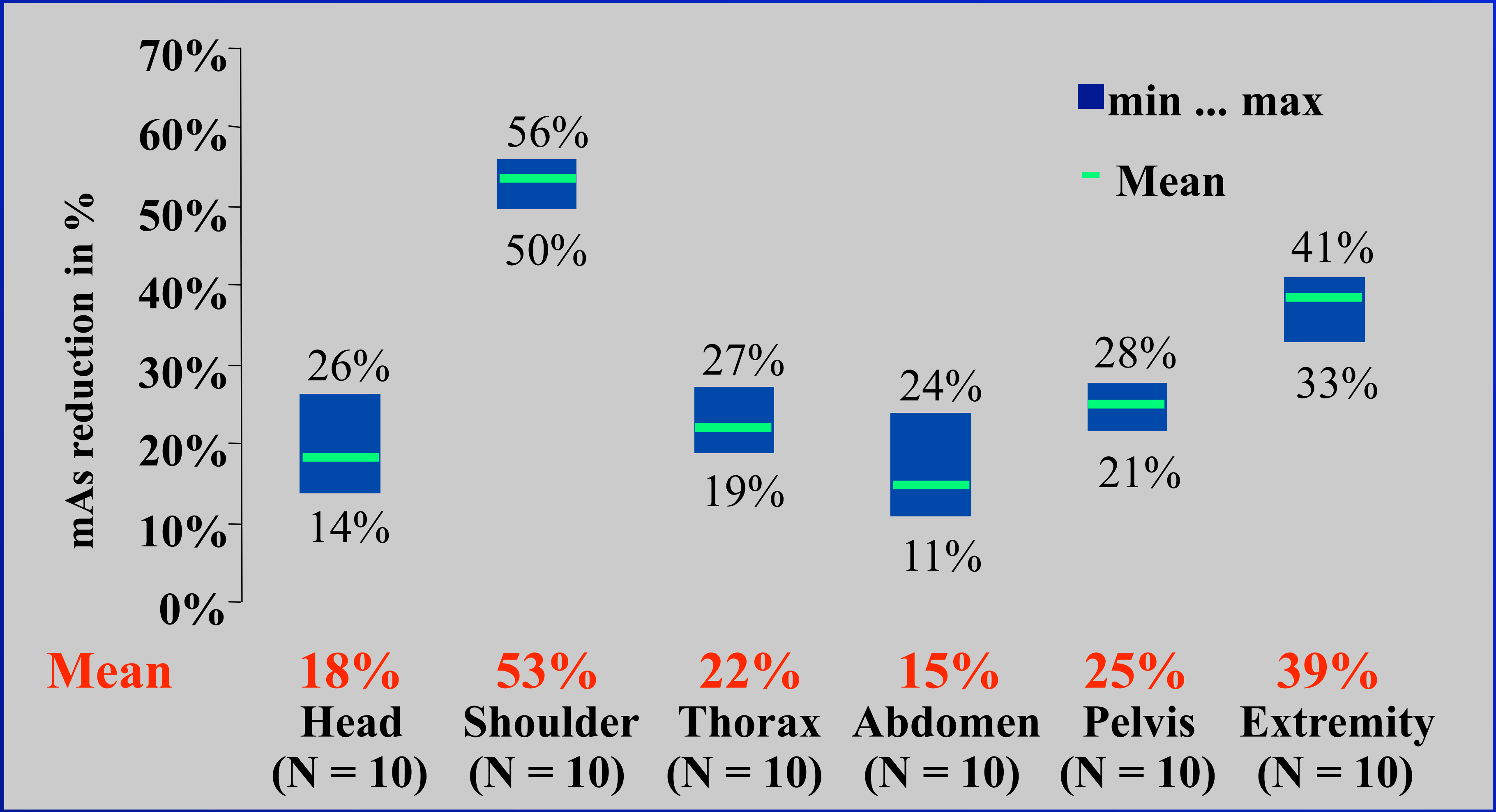
Conventional scan: 327 mAs

Online current modulation: 166 mAs

53% mAs reduction on average for the shoulder region
49% mAs reduction in this case

Kalender WA et al. Med Phys 1999; 26(11):2248-2253

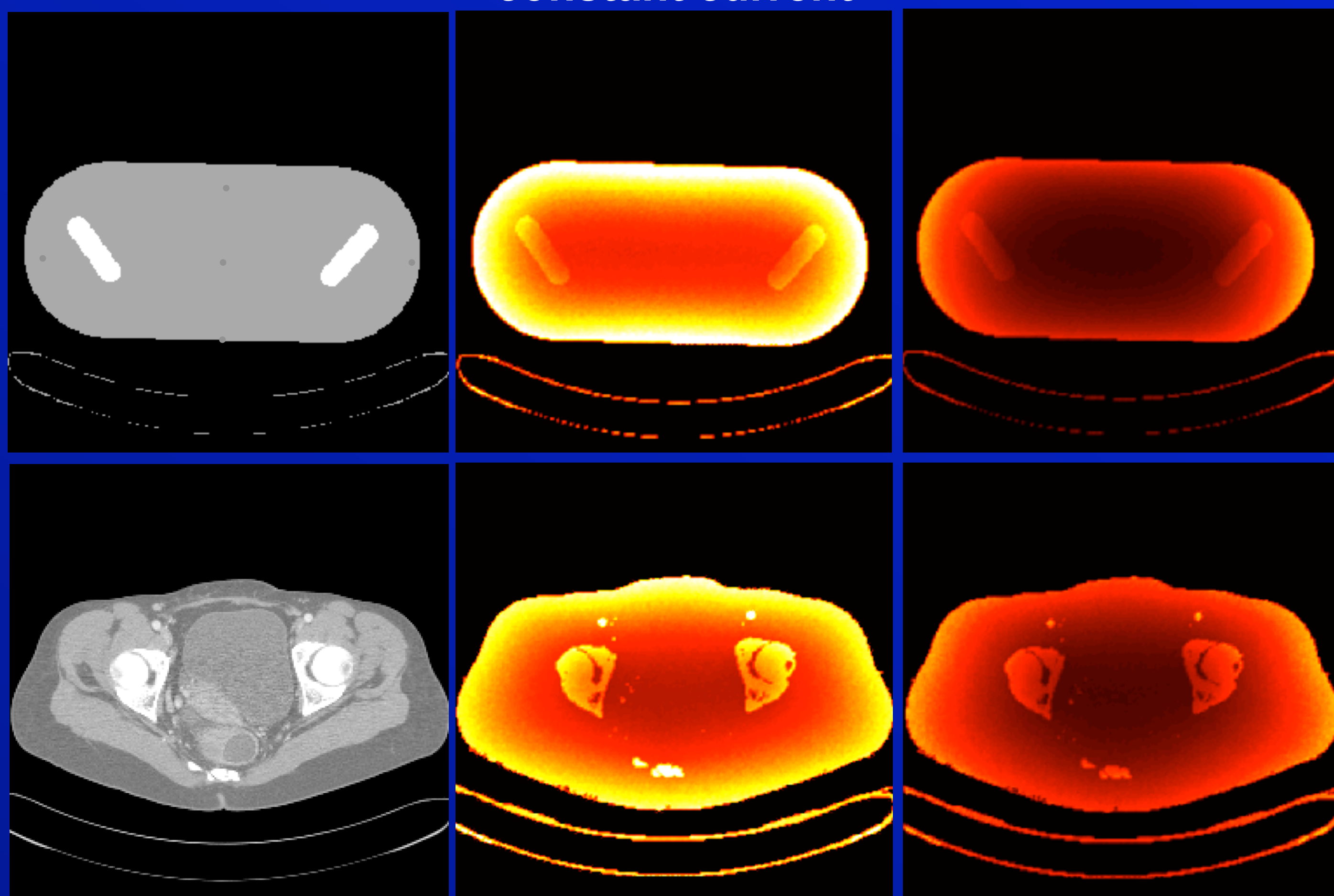
Reduction of mAs for different regions in direct comparison



Grees H. et al. Eur Radiol 1999; 9:323-328

mAs Reduction vs. Patient Dose Reduction

CT image | Dose distribution: constant current | modulated current



Hip phantom
16 cm x 38 cm

0.0 mGy/mGy 0.4

mAs reduction 46%

dose reduction in center 67%

Patient study
ca. 22 cm x 38 cm

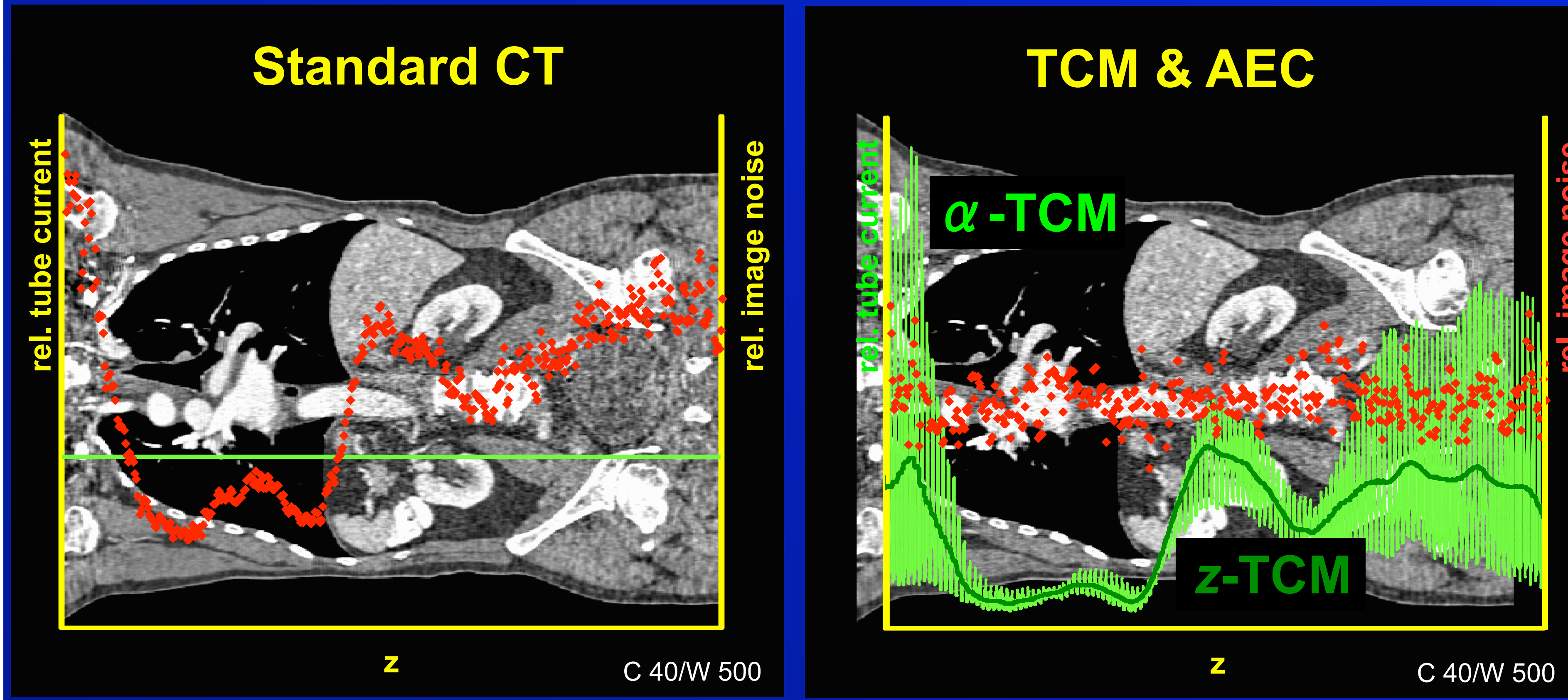
0.0 mGy/mGy 0.6

mAs reduction 43%

dose reduction in center 66%

Kalender WA. Computed Tomography. Wiley, New York 2001

Tube Current Modulation (TCM) and Automatic Exposure Control (AEC)

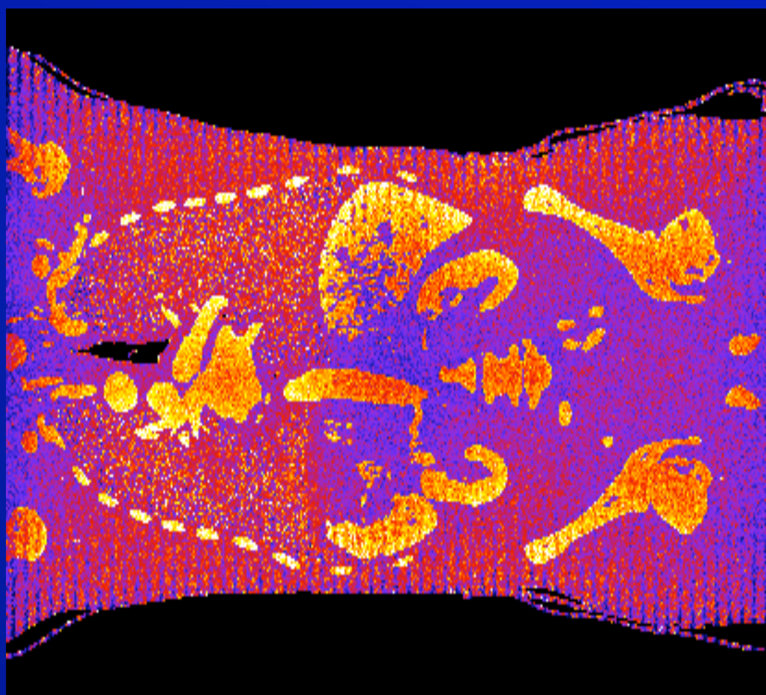


Principle of operation

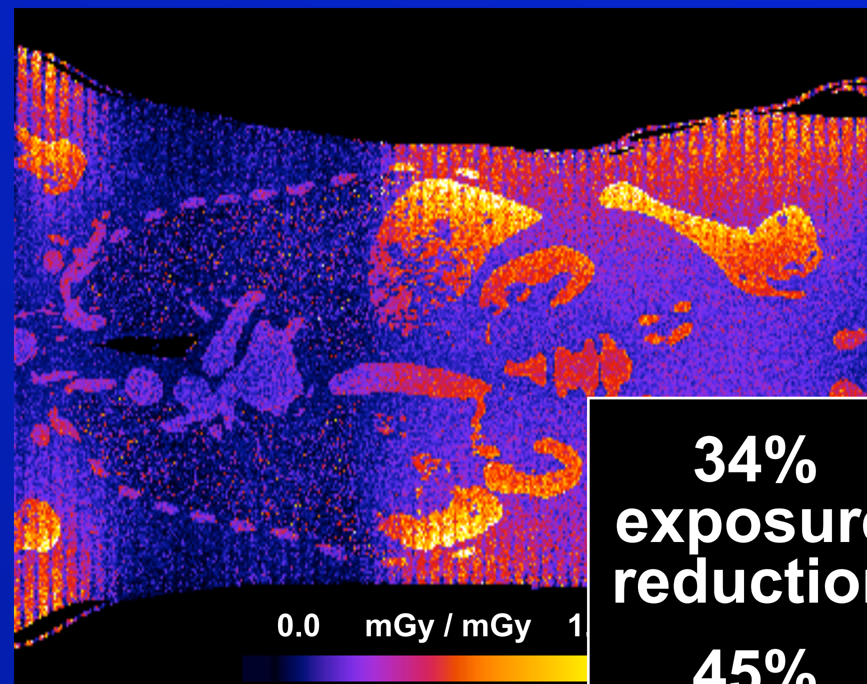
Detectors with smaller z-extent yield better performance!

Kalender WA. Computed Tomography. 2nd ed. Wiley, New York 2005

Tube Current Modulation (TCM) and Automatic Exposure Control (AEC)



Constant tube current



AEC

34% exposure reduction

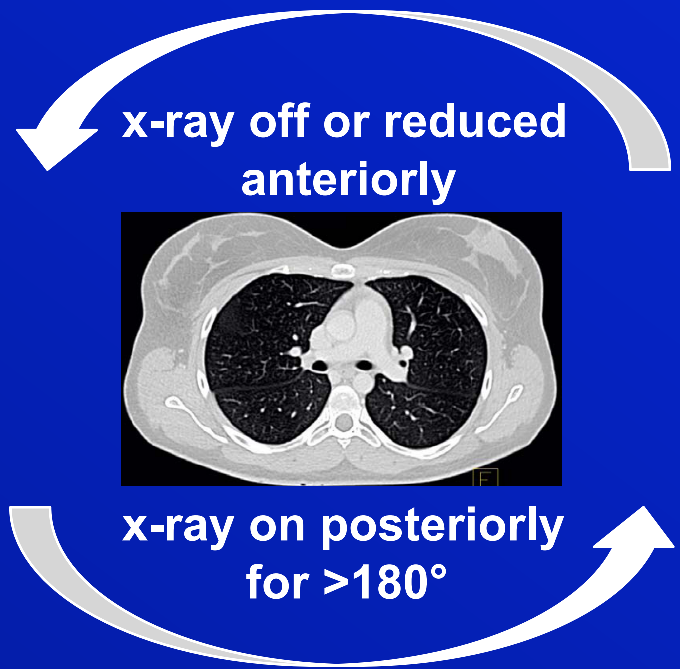
45% dose reduction (center)

Resulting 3D dose distributions

Tube current modulation (TCM)

can be applied as a function of

- rotation angle α (in-plane)
- longitudinal position z
- organ at risk, e.g. breast
- heart phase (ECG)



Conclusions on TCM and AEC

- Adapt the tube current to the size of the patient to be imaged.
- The choice of voltage and filtration, „auto-kV“, has to be a part of doe mamangement.
- Make sure it becomes widely available and actually used.

Dose reduction potential

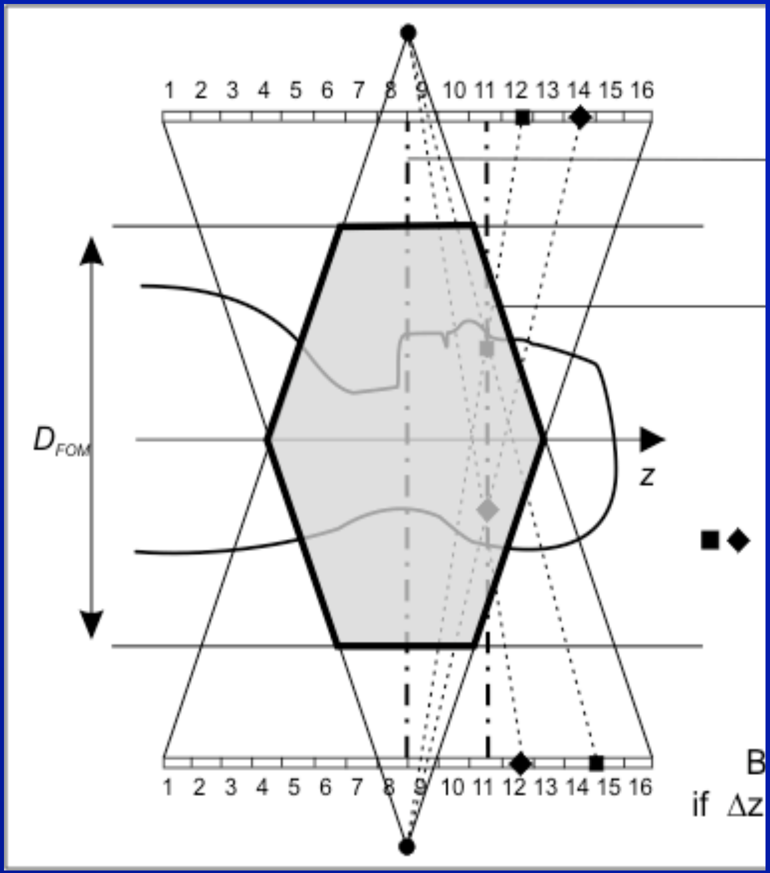
	%	factor
• X-ray sources	20	0.8
• X-ray detectors	30	0.7
• Dose management	30	0.7
• X-ray beam collimation		

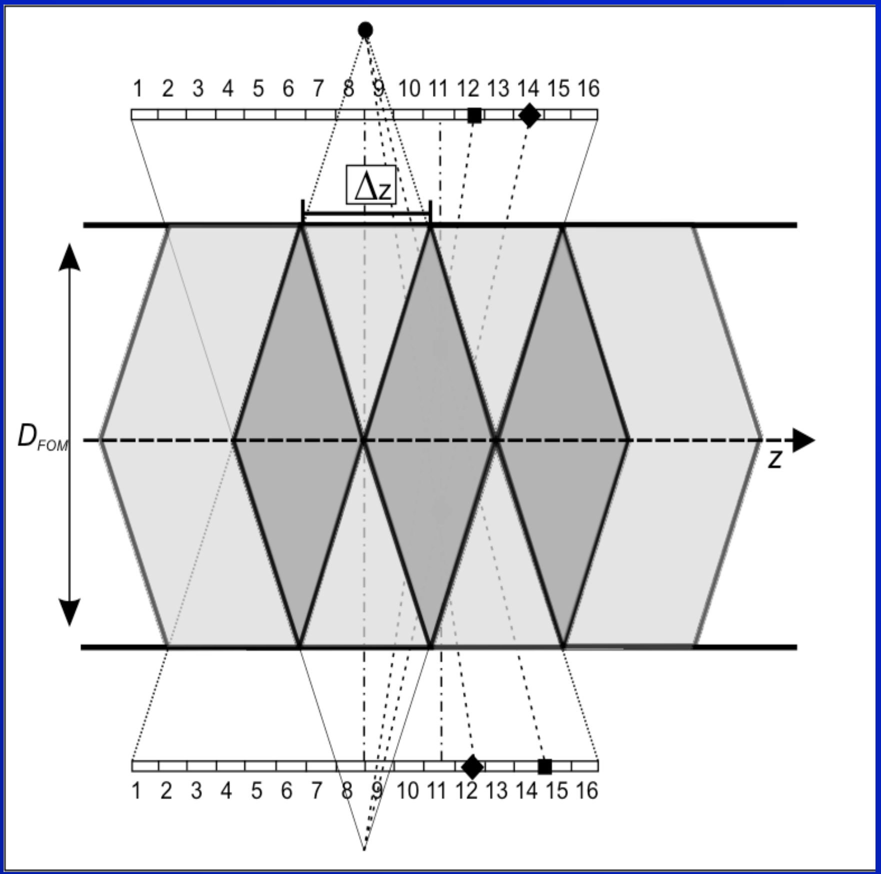
Innovations Required in Hardware

- Definition of goals
- X-ray sources
- X-ray detectors
- Dose management
- X-ray beam collimation
  - dynamic z-overscanning shield
  - volume-of-interest (VOI) scanning
- Conclusions

Overlapping exposure in cone-beam CT

“step & shoot scanning”

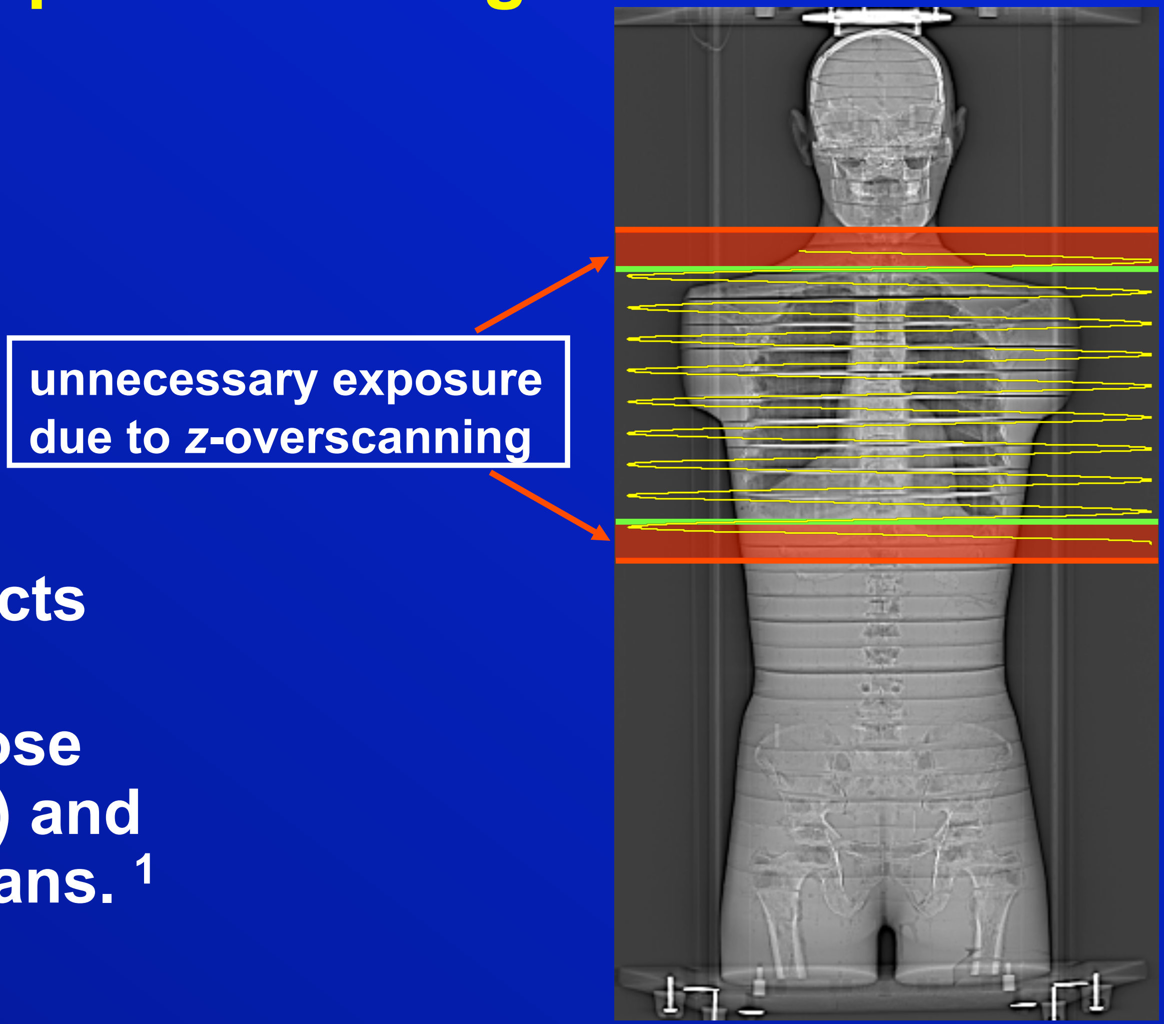




Overscanning exposure in cone-beam CT

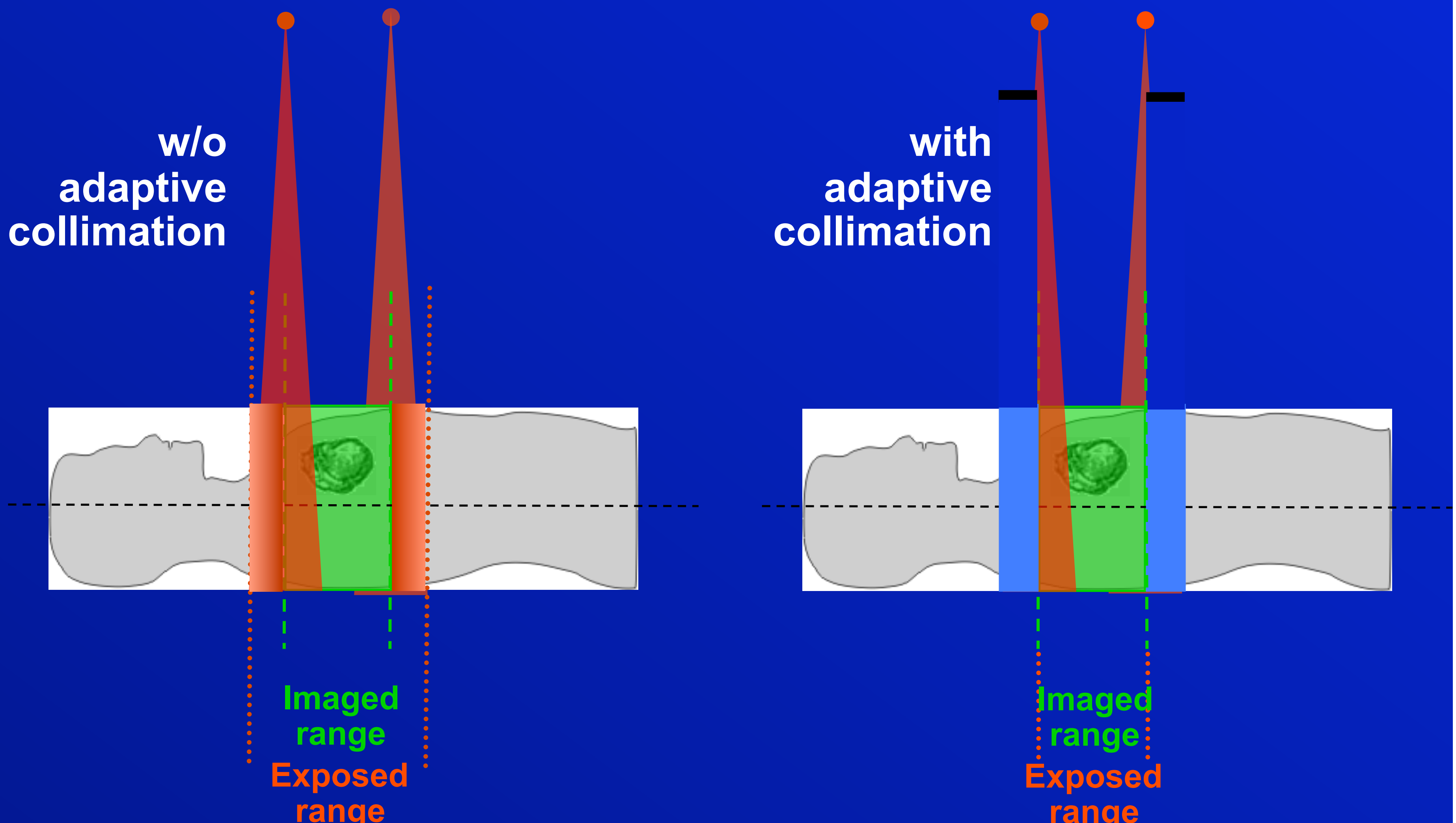
"spiral scanning"

- *z*-overscanning is associated with spiral scanning due to the need for z-interpolation.
- Wider detectors yield higher z-overscanning effects
- Up to 35% higher dose between spiral (p=1) and contiguous axial scans. [1]

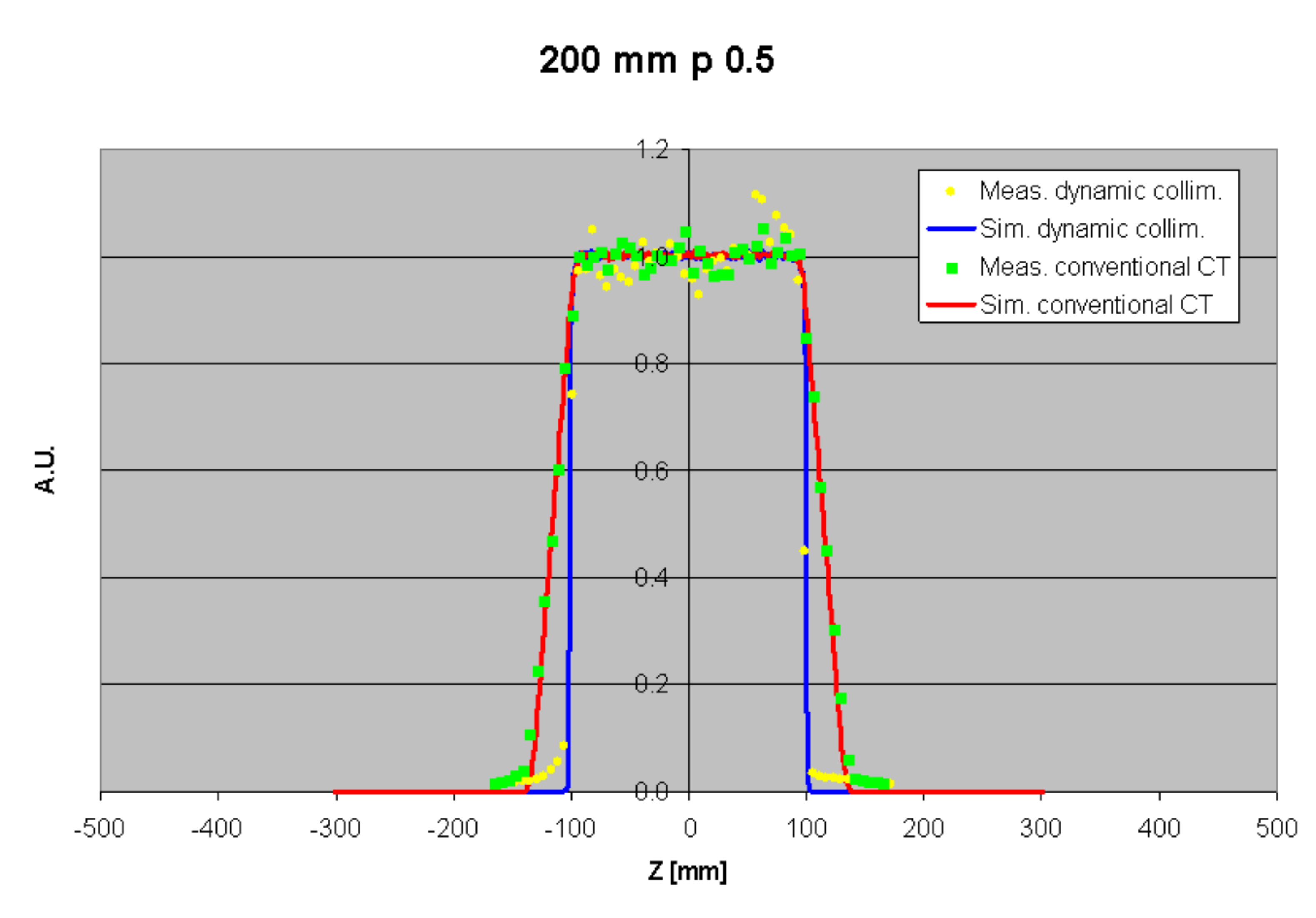


[1]Tzedakis et al. Med Phys 2005; 20:353-59

Overscanning and Counter-Measures

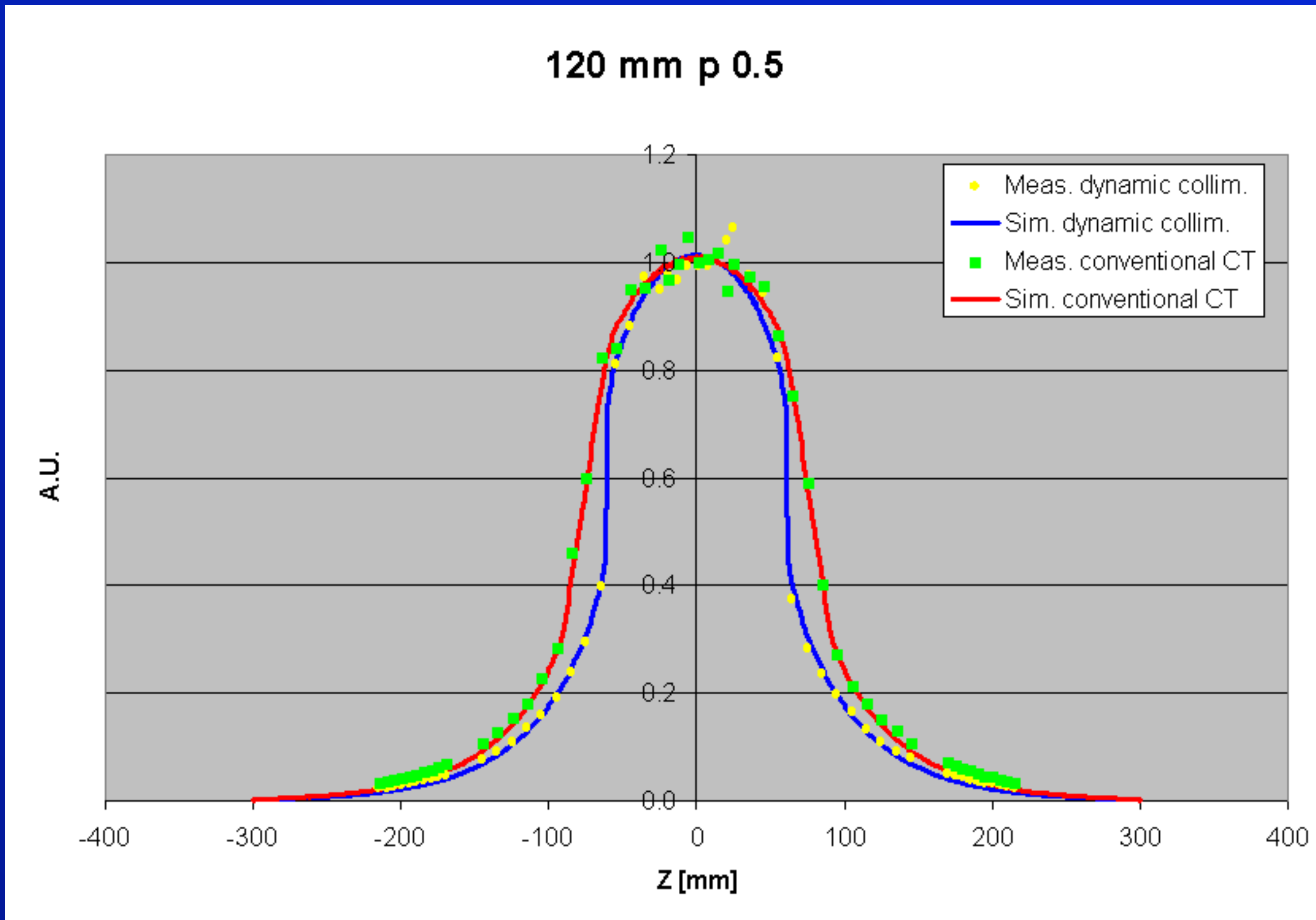


Dose Profiles in Air



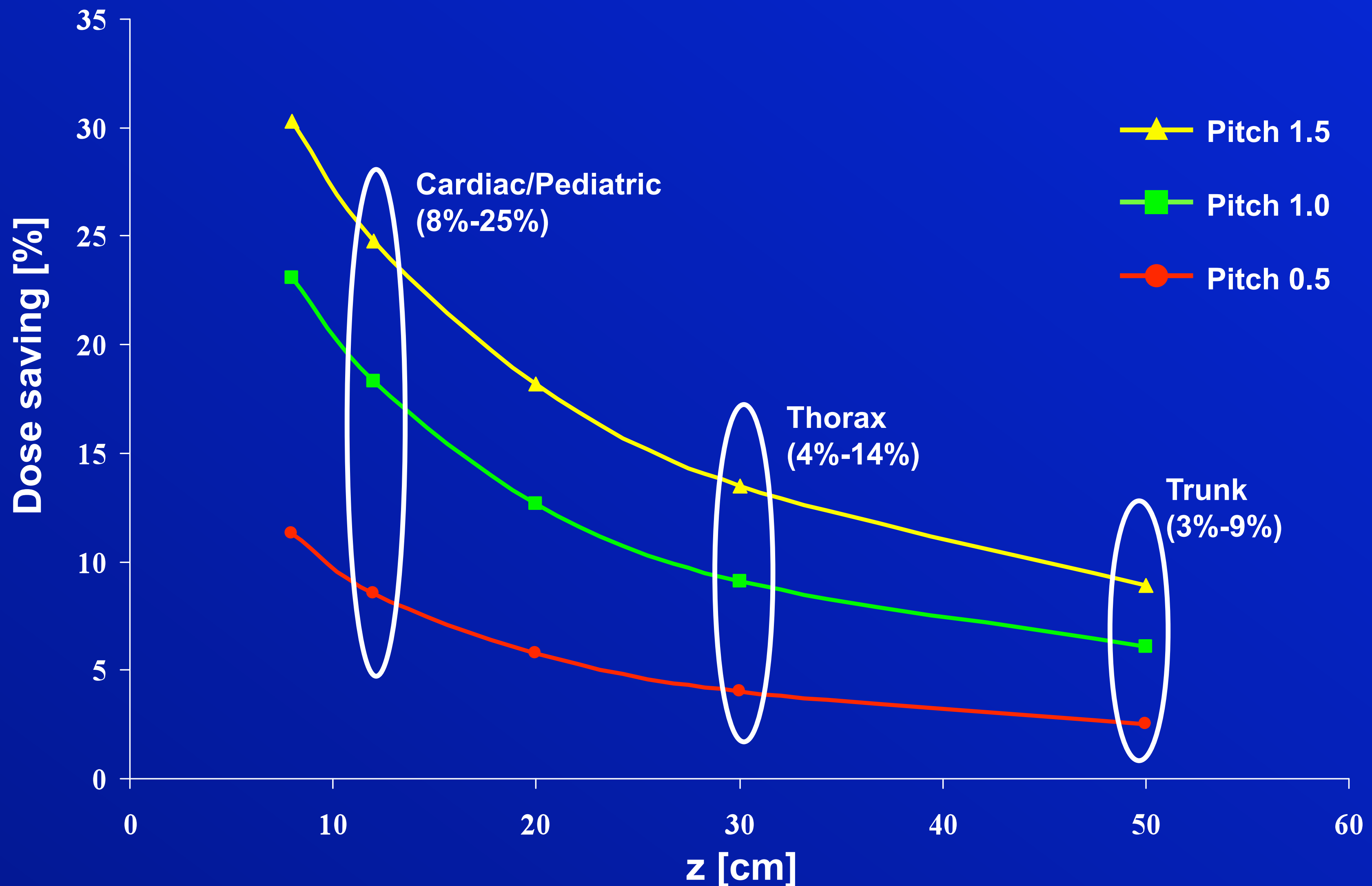
Deak P, Langner O, Lell M, Kalender WA. Radiology 2009; 252:140-147

Dose Profiles in 32 cm CTDI Phantom



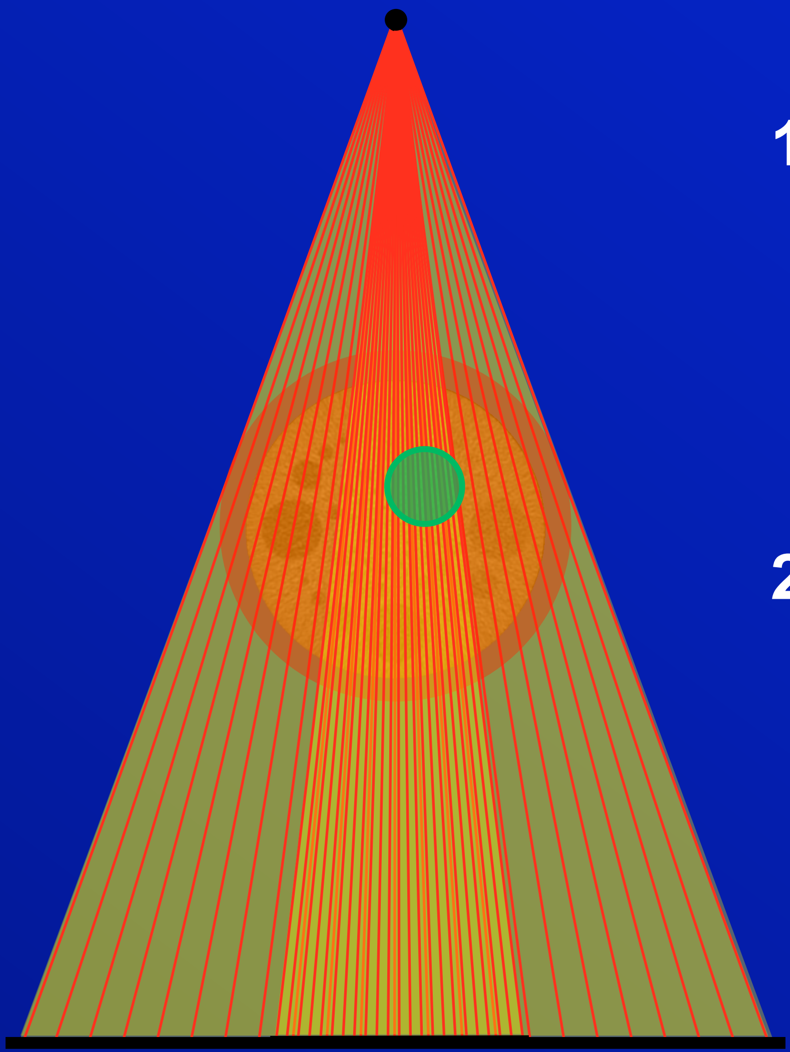
Deak P, Langner O, Lell M, Kalender WA. Radiology 2009; 252:140-147

Results: Dose Saving in Air

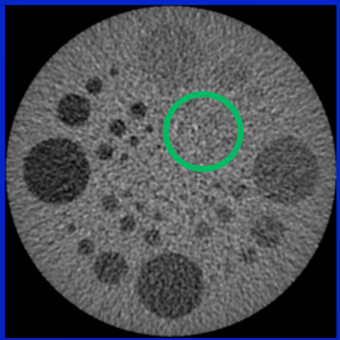


Deak P, Langner O, Lell M, Kalender WA. Radiology 2009; 252:140-147

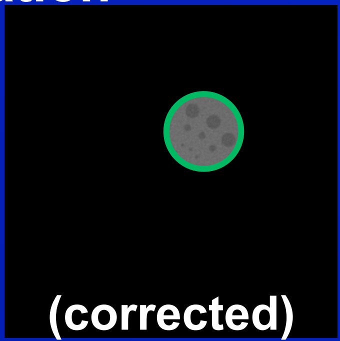
Volume of Interest (VOI) Imaging



1. Overview (OV) scan
   - complete object
   - low dose
   - low image quality
   - VOI selection



2. Volume of Interest (VOI) scan
   - increased collimation
   - increased magnification
   - second isocenter
   - small VOI
   - high local dose
   - high resolution
   - low noise



Kalender WA, United states patent no. US 2008/007525 (2008)

VOI Imaging of a breast phantom (Sim.!)

Overview scan

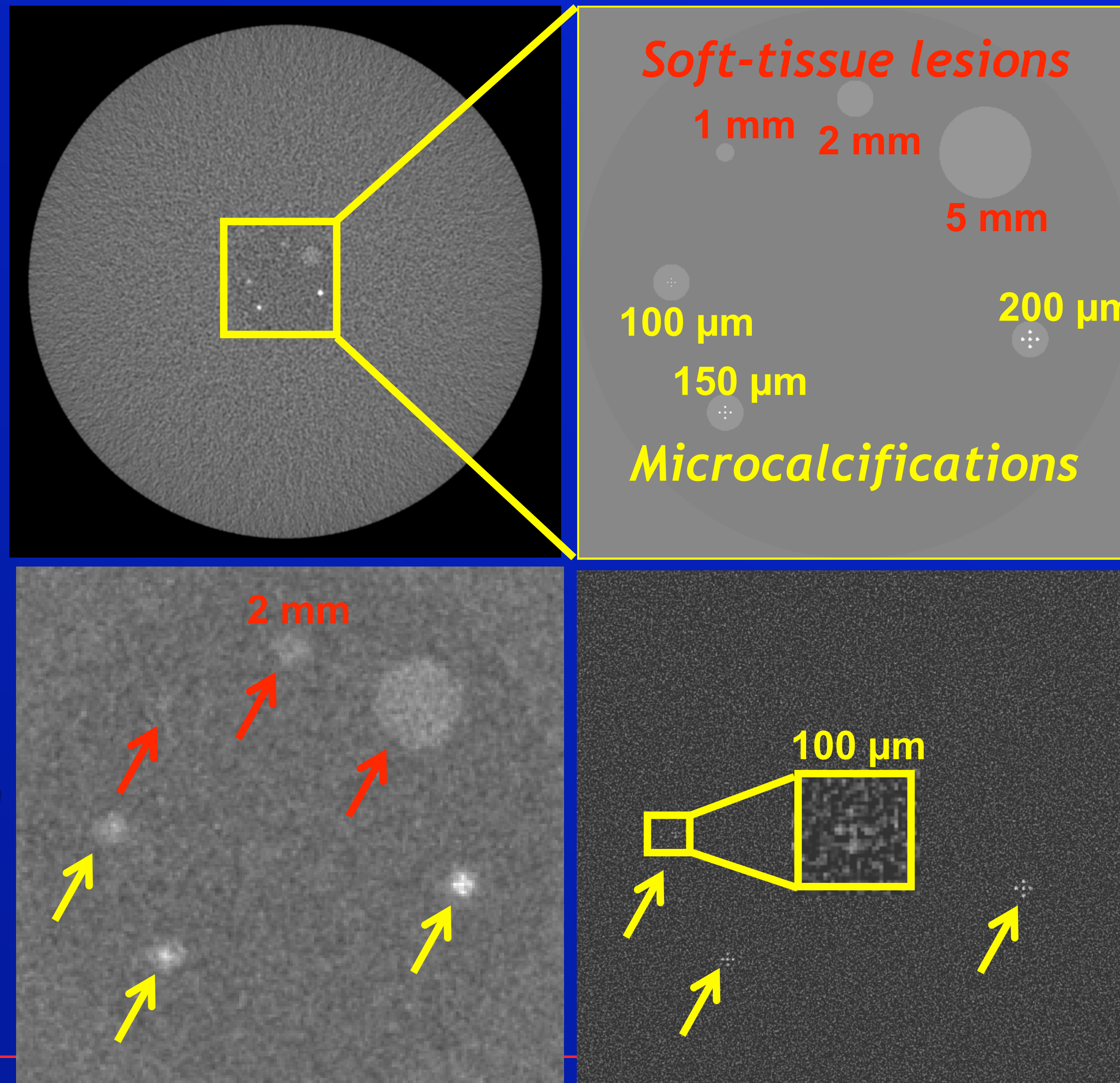
0.75 mm voxels,
1.5 mGy AGD

VOI scan

left: 0.75 mm voxels,
right: 0.05 mm voxels,
1.8 mGy AGD

Cumulative dose

3.3 mGy AGD



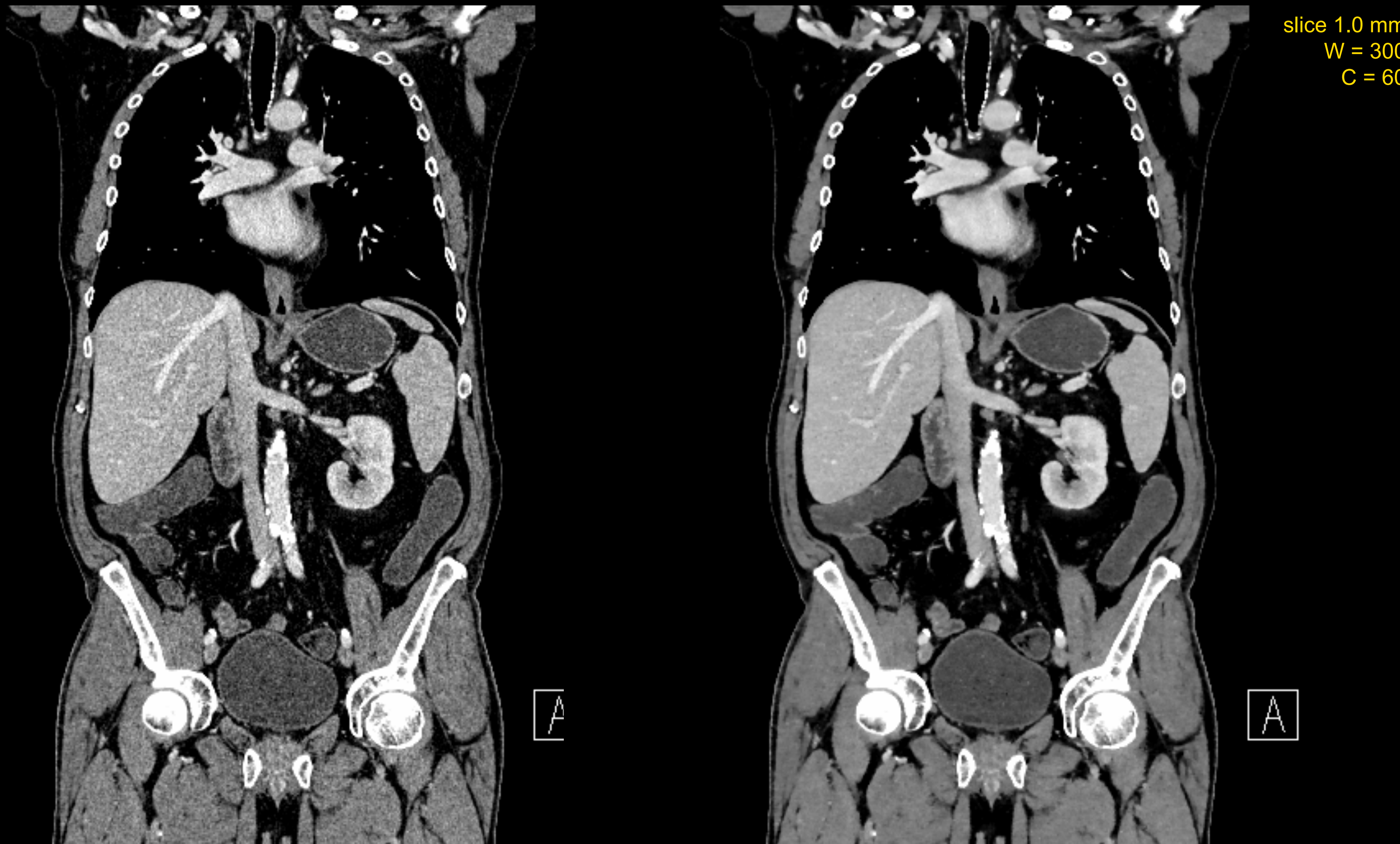
Conclusions on beam collimation

- Limit the exposure to the volume to be imaged by dynamic collimation in z- and ϕ-direction.
- Make sure it becomes widely available and is actually used.

Dose reduction potential

	%	factor
• X-ray spectra	20	0.8
• X-ray detectors	30	0.7
• Dose management	30	0.7
• X-ray beam collimation	20	0.8
• Image reconstruction	40	0.6
Total result	80	0.2

Dose-efficient Image Reconstruction



Standard B40 SAFIRE S40

Courtesy Siemens Healthcare IM CT R&D PA

State of the art & Goals

- Sub-mSv scanning has become a reality for a few applications already.
- The goal of sub-mSv CT scanning, can be reached within this decade!
- It is not only the hardware, training & education are a necessicity!
- There will be new CT applications, e.g. dedicated CT of the breast, and they will operate in the sub-mSv range!


Thank you for your attention!
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